LOAD-CARRYING EFFICIENCY OF HOMOGENEOUS WOOD COMPOSITES[1]

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ABSTRACT

Load-carrying efficiency is defined here on the basis of load-carrying capacity of a composite board per unit weight. Relationships are derived for evaluating the load-carrying efficiency for tension, compression, shear, and bending applications. As an illustration of the application of the theory, limited experimental data are provided for both particleboard and fiberboard to illustrate that optimum load-carrying efficiency does not necessarily occur at the highest density at which these composites can be manufactured. Further, it is shown that optimum load-carrying efficiency varies for different products and load types. These optimum points may not occur at the highest strength and stiffness values attainable for these products.

Keywords: Pseudotsuga menziesii, particleboard, fiberboard, composition board, strength, stiffness, modulus of elasticity, specific gravity, compression strength, models.

INTRODUCTION

Composite boards encompassing such products as flakeboard, chipboard, and fiberboard are used more and more in products where the load-carrying capacity of the product is of primary importance. More and more of these products are "engineered" for load-carrying functions and the strength properties of these products need to be known. Structural applications are becoming more frequent for these materials as witnessed by current research activities to develop a structural composite board.

One advantage of composite boards over solid sawn wood is that they can be engineered to meet certain strength and stiffness requirements. Manufacturing activities should be conducted with optimum efficiencies keeping in mind not only the minimization of production cost but also the optimization of the cost it takes to produce a product that has the highest load-carrying capacity per unit cost. This paper deals with a technique by which optimum material efficiency for such a purpose can be determined.

REVIEW OF LITERATURE

Since the inception of wood composite boards, manufacturers have been interested in improving the various mechanical properties of these products. Activities have concentrated on the effect of such variables as species (Hse et al. 1975; Nelson 1973), particle geometry (Brumbaugh 1960; Plath 1971; Post 1961), and manufacturing variables (Hse et al. 1975; Strickler 1959; Suchsland and

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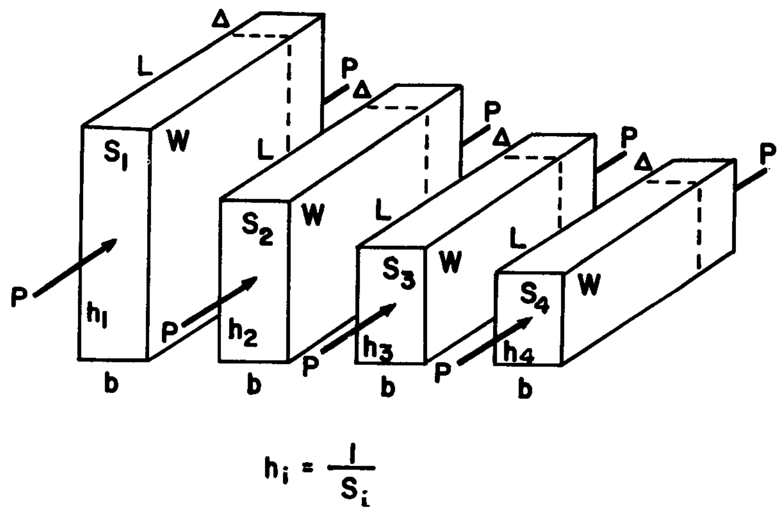

FIG. 1. Specific load-carrying capacity conditions for axial loading.

Woodson 1976). With the increased cost of adhesives, resin efficiency in composite boards became the major target of research (Lehman 1970; Lehman and Hefty 1973; Maloney 1970). While resin content, due to its relatively high cost, is often optimized for a given product, the same cannot be said about the wood component. Innovations in product modification by polymer impregnation (Beall et al. 1975), particle orientation (Talbott 1974; Talbott and Stefanakos 1972) or layering (Bryan 1962; Maloney 1970; Plath 1971; Plath and Schnitzler 1974; Woodson 1976) all can contribute to an improved and more efficient composite product.

Generally, the specific gravity of a given board type is considered the most reliable indicator of the mechanical properties of these products (Hofstrand 1958; Plath and Schnitzler 1974; Woodson 1976; Woodson 1977). Modeling of components (Brown 1975; Bryan 1962; Hunt and Suddarth 1974; Jayne 1972; Plath 1971; Plath and Schnitzler 1974) greatly enhanced the understanding of the factors controlling the mechanical properties of composite boards.

Applications of wood composite boards in engineered structures are increasing steadily. Work to develop design stresses (McNatt 1970; Pearson 1977) is evident as are design considerations for various applications (Lundgren 1957; Superfesky and Ramaker 1976). With the availability of modern structural analysis techniques to model floor, roof (Goodman et al. 1974), and wall (Polensek and Atherton 1976) sections of light frame residential structures, designing with composite boards can be easily incorporated, provided that the proper material and connector parameters are established. Information on such properties as axial and bending strength and stiffness, connector slip behavior, and gap characteristics at the edges of boards and their variability is needed.

SPECIFIC LOAD-CARRYING CAPACITY

Specific load-carrying capacity is defined as the amount of load a unit weight of material can carry under a given set of conditions. The higher the specific load-carrying capacity, the more efficient the material is for structural applications.

Derivation of the relationship for the specific load-carrying capacity is straightforward. First, visualize an axial loading case as illustrated in Fig. 1. Consider four rods (or any other number) of different products with different specific gravities but all having a unit weight, W, length, L, and width, b. The height of these rods, h_i, has to vary inversely with specific gravity to maintain equal weights.

Considering the defined geometries, the height of a rod has to be inversely proportional to its specific gravity, i.e.:

$$h_i \propto \frac{1}{S_i} . \qquad [1]$$

The ultimate load-carrying capacity, P_{ui}, is equal to the ultimate axial stress, σ_{ui}, times the corresponding cross-sectional area, A_i; thus,

$$P_{ui} = \sigma_{ui} A_i = \sigma_{ui} b h_i . \qquad [2]$$

Since for comparative purpose the width in [2] is chosen to be unity, after simplification and substitution of [1] into [2],

$$P_{ui} = \sigma_{ui}/S_i . \qquad [3]$$

Thus, the specific load-carrying capacity for an axially loaded rod with uniaxial strength limitation is the ratio of the ultimate axial stress over the specific gravity of the material. This relationship applies for axial tension and compression as long as no buckling takes place for the latter.

Because of the similar relationship for the case when the shear force is acting in the cross-sectional area,

$$P_{ui} = \tau_{ui}/S_i , \qquad [4]$$

where:

τ_{ui} = ultimate shear stress of the i-th density material in the cross-sectional plane.

In many applications the axial deformation rather than the ultimate load is of significance. Elastic axial deformation is governed by Hooke's law:

$$P_\delta = \frac{\Delta E A}{L} , \qquad [5]$$

where:

P_δ = axial load corresponding to a given deformation, Δ
Δ = axial deformation
E = modulus of elasticity in axial stress
A = cross section
L = length.

For the axial load (Fig. 1) with L = 1 and b = 1, [5] becomes

$$P_{\delta i} = \Delta_i E_i h_i . \qquad [6]$$

It is possible to compare material efficiency at any level of elastic deformation. Thus, for convenience we may choose $\Delta = 1$. Consideration of equality in [6], and substitution of [1] results in

$$P_{\delta i} = E_i/S_i . \qquad [7]$$

For shear consideration with similar assumptions as for axial deformation E_i

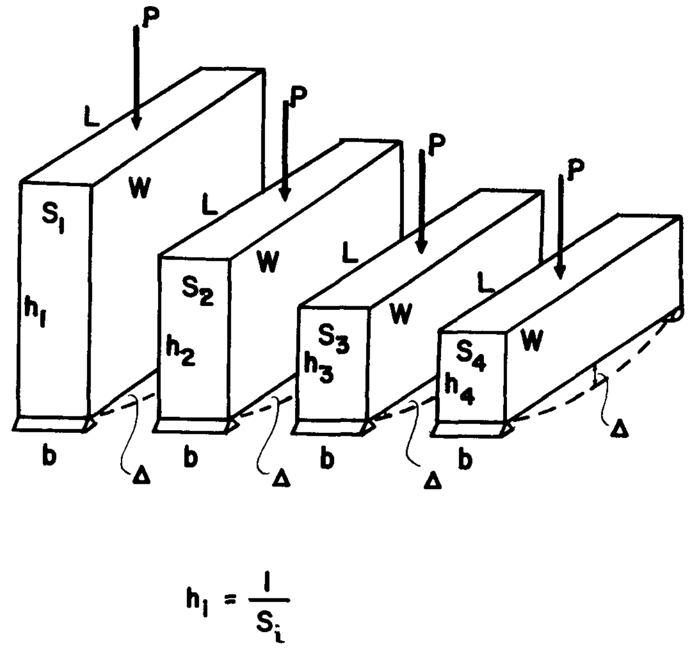

FIG. 2. Specific load-carrying capacity conditions for bending.

is replaced by the appropriate modulus of rigidity, G_i, producing

$$P_{\delta i} = G_i/S_i. \qquad [8]$$

Thus, [3] and [7] can be used to evaluate the specific load-carrying capacity in axial loading and [4] and [8] for shear.

Specific load-carrying capacity in bending (Fig. 2) requires the derivation of different sets of relationships. Using the previously assumed geometry-specific gravity relationships, the ultimate load-carrying capacity can be obtained from the ultimate moment-carrying capacity, M_{ui}:

$$M_{ui} = (MOR)_i I_i/(h_i/2), \qquad [9]$$

where:

$(MOR)_i$ = modulus of rupture
I_i = moment of inertia = $bh_i^3/12$.

However,

$$M_{ui} = \frac{P_{ui}L}{K_j}, \qquad [10]$$

where:

K_j = constant for condition j, with its numerical value varying for different loading conditions and material properties.

Equating the M_{ui} relationships with unit length and unit width and using the I_i expression, the ultimate load-carrying capacity is expressed as:

$$P_{ui} = K_j(MOR)_i h_i^2. \qquad [11]$$

Finally, utilizing [1]

$$P_{ui} = K_j(MOR)_i/S_i^2. \qquad [12]$$

The ultimate specific load-carrying capacity of a material in bending is again a function of the ultimate stress and specific gravity. However, here the square of the specific gravity is required.

For a bending member limited by its elastic deflection, Δ_i, the well-known maximum deflection expression can be used to obtain the ultimate load-carrying capacity:

$$P_{\delta i} = \frac{K_j\Delta_i(MOE)_i I_i}{L^3}, \qquad [13]$$

where:

Δ_i = elastic deflection corresponding to $P_{\delta i}$
$(MOE)_i$ = modulus of elasticity in bending.

Again, considering [1] and unit length, width and deflection, [13] simplifies to

$$P_{\delta i} = K_j(MOE)_i/S_i^3. \qquad [14]$$

Therefore, the specific load-carrying capacity of a bending member based on elastic deflection is a function of its bending modulus of elasticity and the cube of its specific gravity.

GENERALIZED RELATIONSHIPS

The previously desired relationships were obtained through the development of specific examples. These relationships can be generalized for wider applicability. From [3], [4] and [12], it can be seen that the specific load-carrying capacity for load limitations is a function, $\bar{F}$, of stress, σ, (either normal or shear) and specific gravity, S,

$$P_{ui} = K_j\bar{F}(\sigma, S). \qquad [15]$$

Similarly, from [7], [8] and [14] the specific load-carrying capacity when a deformation limit is imposed is

$$P_{ui} = K_j\bar{G}(C, S), \qquad [16]$$

where:

C = compliance parameter corresponding to a specific deformation condition.

Since it was demonstrated earlier in the derived relationships that specific gravity appears as a divisor with a certain exponent, [15] and [16] respectively can be further refined to the form:

$$P_{ui} = K_jS^{-n}F(x), \qquad [17]$$

where:

x = appropriate stress or compliance parameter.

It has been demonstrated frequently in the literature and also illustrated in Figs. 3 through 6 that the various ultimate stress and compliance parameter values are functions of the specific gravity of the material they represent. Therefore, [17] can be written to represent the relationship:

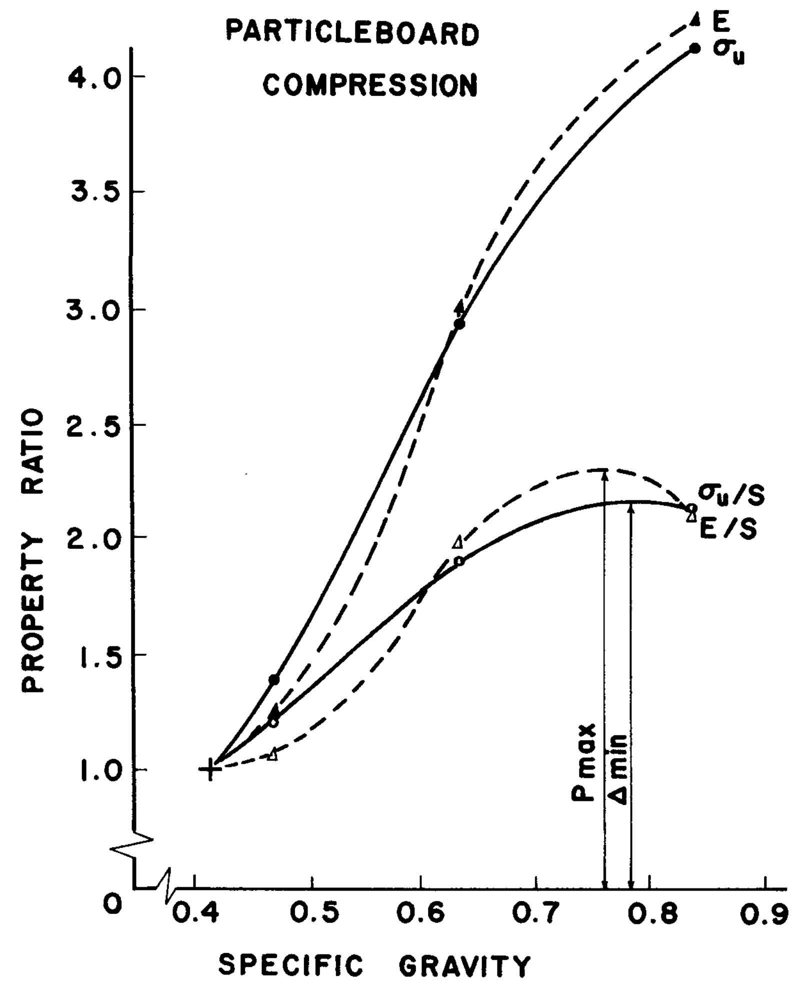

FIG. 3. Relationship between property ratio and specific gravity of particleboard in compression.

$$P_{ui} = K_j S^{-n} f(S), \qquad [18]$$

where the function of material property f(S) has to be determined from measurements and can be a linear or exponential function.

The most efficient material utilization is obtained when P_{ui} is maximum. This maximum can be obtained by differentiating [18] with respect to specific gravity and equating the result to zero.

$$\frac{dP_{ui}}{dS} = \frac{d}{dS}[K_j S^{-n} f(S)] = 0. \qquad [19]$$

COMPOSITE BOARD EXAMPLES

The principles previously presented are independent of the material used. Thus, only a limited experimental design was carried out to illustrate the applicability of these principles to manufacturers of composite products. Four panels of a

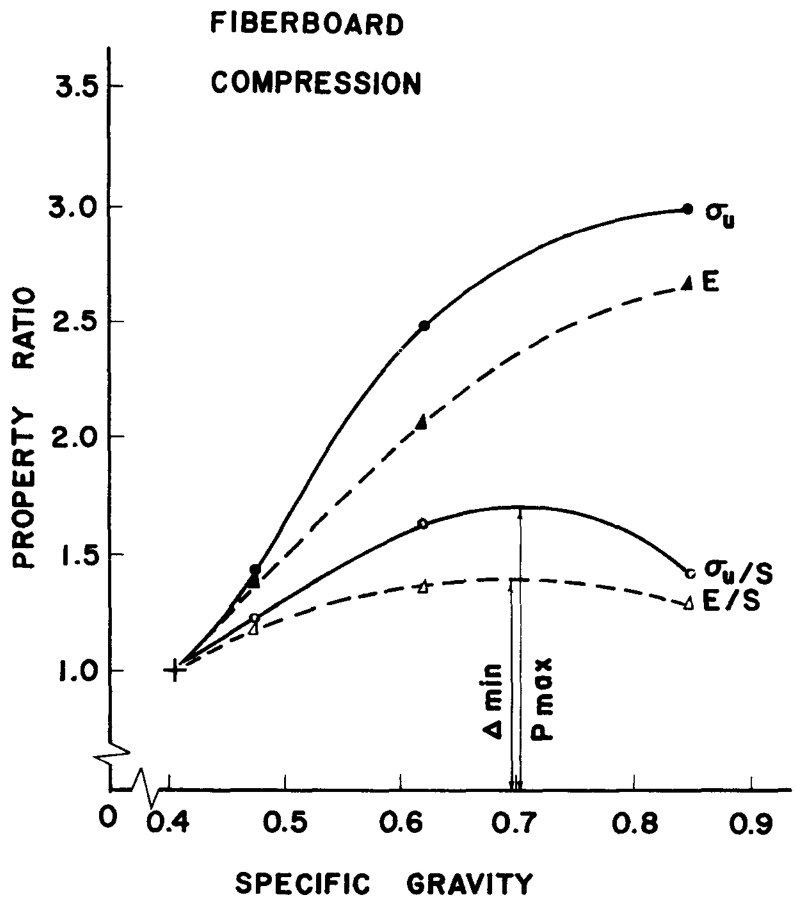

FIG. 4. Relationship between property ratio and specific gravity of fiberboard in compression.

laboratory type particleboard were manufactured for the demonstration. Obviously a manufacturer wishing to evaluate his commercial product would carry out a much more extensive experimental design. A single batch of furnish of lodgepole pine planer shavings was sprayed with urea-formaldehyde resin (6% solid glue/oven-dry wood). From this sprayed furnish, four portions of equal weight were taken to form single 2- by 2-foot panels. The pressing schedule used was sufficiently long as determined by thermal conductivity computations and the adhesive manufacturer's recommendations to insure curing of the resin throughout the panel. The only difference between panels was the pressing pressure employed and the longer time needed in the press for curing the thicker panels.

Thus, from equal weights of furnish, different board thicknesses and specific gravities were produced (Table 1). A similar procedure was used to produce fiberboards (from commercial furnish Douglas-fir fibers using again 6% urea-formaldehyde resin) of different thicknesses and specific gravities as shown in Table 1. The purpose of this approach was to demonstrate that the same amount and quality of furnish can produce different specific load-carrying capacities.

From each panel, conditioned to approximately 12% moisture content, two

TABLE 1. *Specific load-carrying capacity data.*

			Compression				Bending			
Panel	h (in.)	S —	σ_u (psi)	σ_u/S	E (10⁶ psi)	E/S	MOR (psi)	MOR/S²	MOE (10⁶ psi)	MOE/S³
					Particleboard					
A	0.882	0.418	583	1,395	0.0540	0.129	551	3,153	0.1282	1.756
B	0.769	0.479	809	1,689	0.0658	0.137	782	3,409	0.1680	1.529
C	0.581	0.634	1,685	2,658	0.1629	0.257	1,417	3,525	0.2567	1.007
D	0.441	0.835	2,488	2,980	0.2298	0.275	1,752	2,513	0.3687	0.633
					Fiberboard					
A	0.732	0.405	927	2,289	0.1840	0.454	883	5,384	0.1011	1.523
B	0.616	0.475	1,325	2,789	0.2532	0.533	1,366	6,055	0.1398	1.381
C	0.473	0.619	2,295	3,708	0.3772	0.609	2,692	7,025	0.2314	0.976
D	0.345	0.849	2,760	3,251	0.4917	0.579	5,014	6,956	0.4617	0.754

bending and four compression samples were tested according to ASTM Designation D-1037, (1972). Compression specimens were glued together to produce square cross sections. Test results and specific gravity values were utilized to compute the specific load-carrying capacity values as previously defined in [3], [7], [12] and [14] (Table 1).

A relative change in the specific load-carrying capacity is easier to evaluate than the actual number. Thus, particleboard and fiberboard panels "A" were designated as reference values. Computed ratios are tabulated in Table 2. Higher ratios indicate better specific load-carrying capacity than that of panel "A"; the reverse is true for lower ratios.

In compression, both particleboard and fiberboard panels exhibited rapid increases for ultimate stress and modulus of elasticity property ratios with increasing specific gravity (Figs. 3, 4). One would conclude from these property ratios that panels should be produced with specific gravities above 0.8. However, the particleboard specific load-carrying capacity ratios for ultimate stress, σ_u/S, and axial deformation E/S reach maximum values at 0.76 and 0.78 specific gravity, respectively. These maximum values are found at 0.70 specific gravity for fiber-

TABLE 2. *Property ratio for specific load-carrying capacity.*

	Compression				Bending			
Panel	σ_u	σ_u/S	E	E/S	MOR	MOR/S²	MOE	MOE/S³
				Particleboard				
A	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B	1.388	1.211	1.219	1.063	1.419	1.081	1.310	0.871
C	2.890	1.905	3.017	1.988	2.572	1.118	2.002	0.573
D	4.268	2.136	4.256	2.130	3.180	0.787	2.876	0.360
				Fiberboard				
A	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B	1.429	1.218	1.376	1.174	1.547	1.125	1.383	0.907
C	2.476	1.620	2.050	1.341	3.049	1.305	2.289	0.641
D	2.977	1.420	2.672	1.275	5.678	1.292	4.567	0.495

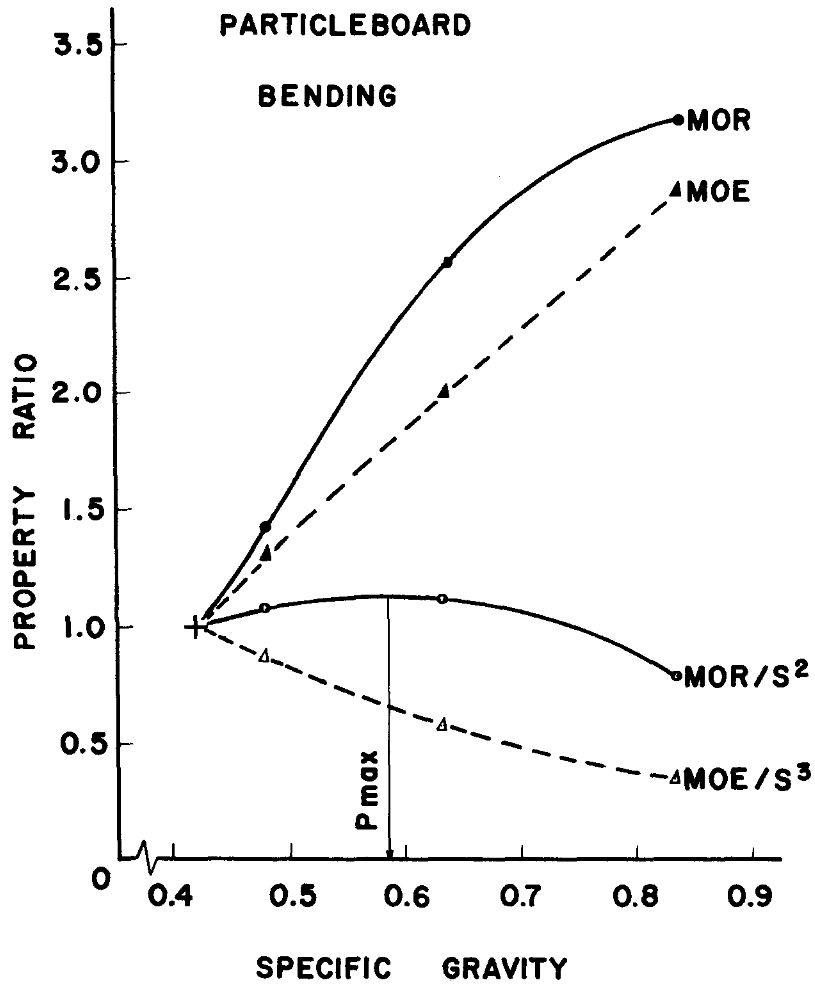

FIG. 5. Relationship between property ratio and specific gravity of particleboard in bending.

board (Fig. 4). Thus, pressing the above laboratory type particleboard to approximately 0.77 and fiberboard to 0.70 specific gravities produces the highest load-carrying efficiencies.

MOR and MOE ratios also increase rapidly with increasing specific gravities for both particleboard (Fig. 5) and fiberboard (Fig. 6). These figures reveal optimum specific gravities for ultimate bending load, MOR/S_i^2 of 0.58 and 0.69 for particleboard and fiberboard, respectively.

No maximum ratio can be found for ultimate load if deflection governs the design, MOE/S^3 (Figs. 5, 6). In this case it appears that the optimum specific gravity values are lower than those for panel A, indicating that the laboratory type composite boards should be pressed to relatively low specific gravities and larger thicknesses if the designs of bending members are governed by deflection. However, for each specific application all three properties—normal stress, shear stress and deformation—have to be evaluated separately to determine the governing property.

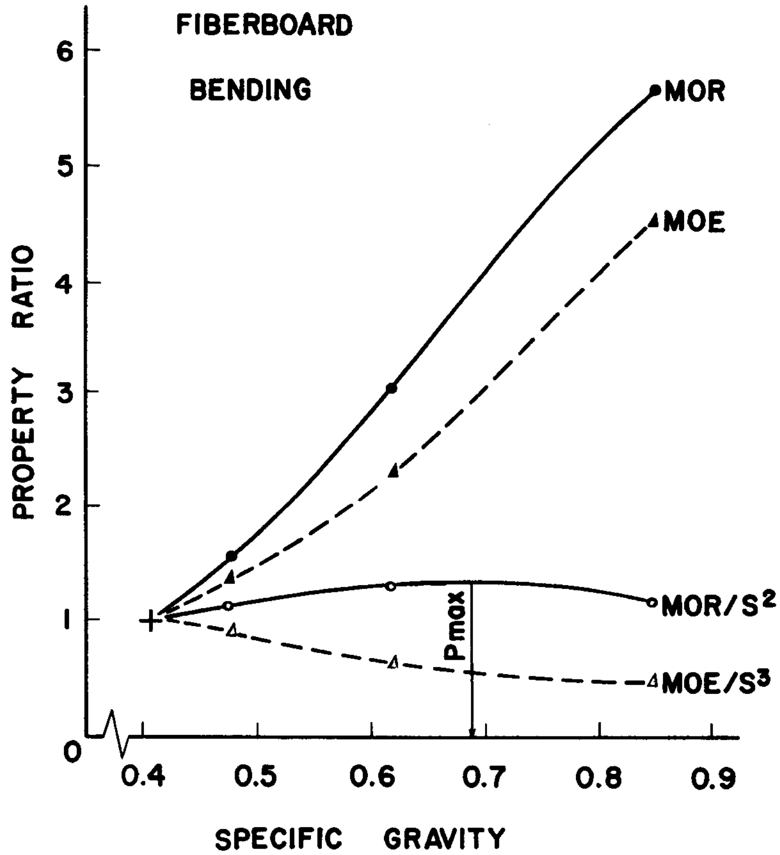

FIG. 6. Relationship between property ratio and specific gravity of fiberboard in bending.

In addition to the graphical solution, which is somewhat less accurate, the numerical technique can be used to evaluate the optimum density of the product for a given end use requirement. Thus, the use of [19] is illustrated here by the obtained numerical data. For example, the MOR-specific gravity relationship for fiberboard (Fig. 6) can be approximated by a linear relationship:

$$f(S) = MOR = -3{,}073.9 + 9{,}306.0S.$$

Further, for MOR n = 2 as given in [12]. While the mode of bending is immaterial to the solution, let us assume that the panel is loaded in simple span bending with a concentrated load at midspan. For this case $K_j = 2/3$. Substitution into [19] results in

$$\frac{dP_{ui}}{dS} = \frac{d}{dS}[2/3 S^{-2}(-3{,}073.9 + 9{,}306.0S)] = 0.$$

After differentiation and simplification, this becomes

$$6{,}147 - 9{,}306S = 0,$$

resulting in an optimum specific gravity value of S = 0.66. This is compared to the value obtained by graphical solution (Fig. 6) of 0.69. The difference is easily explained by the somewhat curvilinear nature of the MOR-S relationship and the lower accuracy of the graphical solution.

DISCUSSION AND SUMMARY

The derived relationships for specific load-carrying capacity are general in nature and applicable to any homogeneous material or loading condition. Examples were given for particleboard and fiberboard loaded in compression and bending. The derived optimum specific gravities are applicable only to the specific laboratory panels investigated. They serve only as illustrative examples showing that optimum load-carrying efficiency does not necessarily occur at the highest specific gravity at which a product can be manufactured. Each commercial product should be studied separately and in more detail to evaluate its own optimum specific gravity.

It should be easy to see that optimum load-carrying capacity may not be attained for every product. Other factors, such as surface hardness, connector holding capacity, and finishing requirements, for example, may alter selection of the optimum specific gravity. These judgments have to be made in light of other end-use requirements of the products. Nevertheless, it would be to the benefit of each producer to evaluate the optimum specific gravity of his products for the most efficient load-carrying capacity and then assess the alterations which are feasible for other requirements.

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